A 4-Hz Fundamental Linewidth on-chip Microlaser

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Abstract: A compact laser source on a silicon chip with Shawlow-Townes linewidth (i.e., fundamental, quantum limited) down to a few Hertz is demonstrated in this work. The fundamental linewidth is observed to decrease with inverse optical power.

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The development of stable and ultra-narrow linewidth laser source sees many applications in coherent communication systems, biosensing devices as well as high-resolution spectroscopy [1,2]. Jiang et. al. have reported a single-frequency fiber laser with record linewidth of 200 Hz [3]. In this work, we demonstrate the first micron-scale on-chip laser having a fundamental linewidth as narrow as 4 Hz. The fundamental linewidth of a laser is given by the Schawlow-Townes formula,

$$\Delta\upsilon = \frac{h\upsilon^3 n_{sp}}{4\pi} \cdot \frac{1}{P} \cdot \frac{1}{Q^2} \qquad (1)$$

where Q is the "cold cavity" quality factor of the laser cavity, P is output power, ν is the optical frequency and n_{sp} is the spontaneous emission factor. Therefore, increasing the cavity Q factor will quadratically reduce the fundamental linewidth at a given power level P. The advent of the microtoroid cavity with quality factors as high as 500 million [4] and recent advances in Erbium-doped lasers using this cavity geometry [5] makes it possible to decrease the fundamental laser linewith to the Hz level at very modest output powers.

The laser is made from Er-doped sol-gel silica spun on a silicon substrate. The microtoroid structure is achieved by CO_2 laser reflow of a sol-gel silica disk, which is fabricated using standard photolithography and buffered HF etching, followed by XeF_2 etching techniques as described elsewhere [4,5]. The ultra-high quality of the device is due to the quick melting procedure during the CO_2 reflow process and subsequent solidification into a toroidal shape due to surface tension. Optical pump power is coupled into the cavity with an efficient fiber taper [6,7] and output laser power is coupled using the same structure. Lasers were selected so as to exhibit simultaneous oscillation on "backscatter-split" optical modes. Backscatter splitting is common in Ultra-high-Q cavities [8], and, occasionally, we have found that lasers based on these cavities will simultaneously oscillate on split lines. This effect provides a convenient way to perform a heterodyne-measurement of phase noise since the common-mode "technical" noise is rejected as the modes share the same cavity.

A schematic of the experimental setup is presented in fig. 1. A tunable laser in the 1460 nm band is used to pump the microtoroid laser. The single-frequency pump laser is isolated using an optical circulator to prevent feedback-induced instabilities. After passing through the polarization controller, the pump wave is coupled into the microtoroid cavity by the fiber-taper. By carefully adjusting the taper-toroid coupling position, two independent lasing modes at optical frequency separation of around 10 MHz are generated and coupled out of the cavity to the taper output end. They are subsequently divided by a 50/50 coupler. The lasing modes and the residual pump laser are monitored by an optical spectrum analyzer. The two lasing modes are further separated from the pump laser by a wavelength de-multiplexer, and detected by a photoreceiver to create a heterodyne beat note. The electrical beat-note signal is then split into two arms, which, after passing through different delay lines, recombine in an RF mixer that is connected into a spectrum analyzer.

The laser linewidth is derived from the phase-noise spectral density observed on the spectrum analyzer. Figure 2a shows the laser spectrum from the microtoroid detected by an Optical Spectrum Analyzer (OSA). The finely split laser modes are not resolved in the spectrum. Other oscillation modes are suppressed by

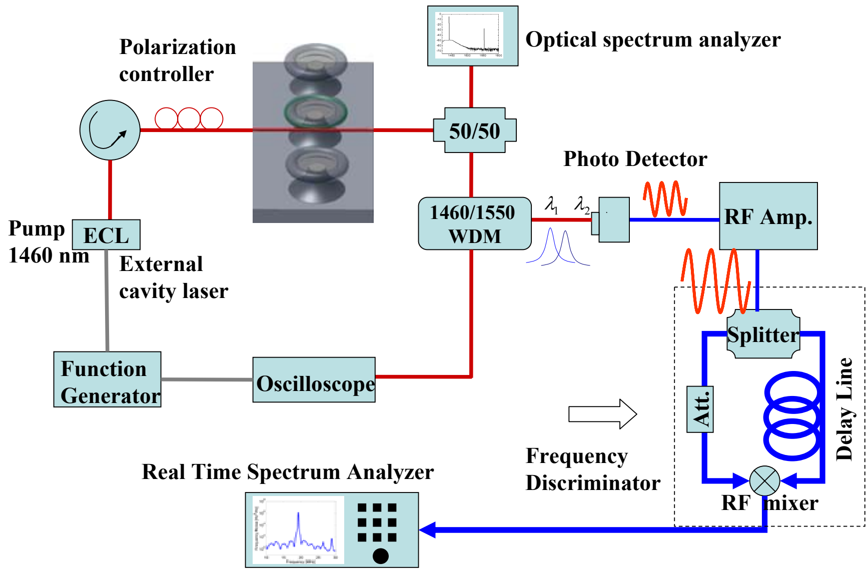
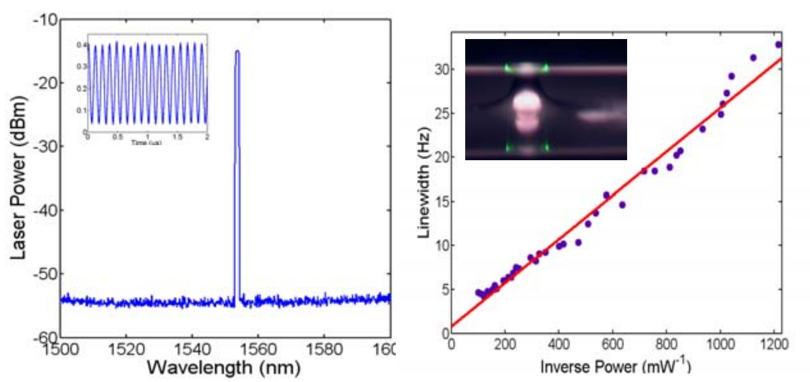


Fig 1. Schematic of the measurement setup.

more than 40 dB. The inset of fig. 2a presents the beatnote from the two lasing modes as observed on an oscilloscope in the time domain. An optical microscope side-view image of a fiber taper coupled microtoroid is shown in the inset of fig. 2b. The device has a diameter of 60 μm and a Q factor of 10^7. The measured fundamental linewidth as function of inverse laser power is shown in fig. 2b. It clearly exhibits the classic, inverse-power dependence expected for the Schalow-Townes linewidth. At the output power of 10 microWatt, the fundamental linewidth decreases to 4 Hz. The measured linewidth is also in close agreement with the theoretically expected value at this Q factor and output power level. This work was sponsored by DARPA.



(a) (b)

Fig 2. a. Laser spectrum . b. Linewidth plotted versus inverse laser power

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